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FINAL REPORT
for
Near-Infrared Imaging of Selected Areas

supported under Contract F19628-91-K-0021

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Statement of Work: The observational program described here consists of multi-color near-infrared imaging of selected areas on the sky. The scientific goals are to provide a database for development of algorithms for efficient extraction of sources both in sparse and in crowded areas, and to check current models of the sky. The practical goals are to test a variety of observing techniques in preparation of a new near-infrared all-sky survey.

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THE TWO MICRON ALL SKY SURVEY

Survey Strategy and Prototyping

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Abstract. This paper describes the design, expectations, and prototyping of a new all-sky survey, called 2MASS (Two Micron All Sky Survey) to be carried out with the new generation of infrared array detectors.

Key words: sky survey – infrared star counts – infrared galaxy counts

1. Introduction

The 2MASS (Two Micron All Sky Survey) project is an effort to obtain a uniform map of the whole sky in the near-infrared. The survey will be executed simultaneously in 3 wavebands, centered at 1.25 (J), 1.65 (H), and 2.16 (K_s) μm, with a pixel size of $2.3'' \times 2.3''$. It will have sufficient sensitivity to measure accurate positions and brightnesses for ~100 million stars and ~1 million galaxies. This survey would not be possible without the new generation of infrared-sensitive array detectors; at the same time, it provides a database that is critically needed in order to apply those arrays to interesting and objectively selected sources to study.

The only existing large-area near-infrared sky survey, the *Two Micron Sky Survey* (Neugebauer and Leighton 1969; hereafter TMSS), reached a

I. McLean (ed.), Infrared Astronomy with Arrays, 219–226.

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I. Significant Accomplishments

This project was aimed at obtaining a near-infrared imaging database of substantial sky coverage, good sensitivity, and wavelenegth coverage, in order to answer a number of questions essential for the planning of a new, near-infrared all-sky survey. (The survey is now called the Two Micron All Sky Survey, or "2MASS", and will begin full operations in 1997.) The need for the observational study described here, prior to the all-sky survey, was driven by the enormous sensitivity difference between 2MASS and the only existing near-infrared sky survey—a factor of more than 50,000! Certainly, the database that existed at the start of this project was insufficient to answer basic questions needed to determine an optimal selection of survey parameters and feasible strategies for data processing.

The work described here was extremely successful, in that specific answers were obtained to all of the questions originally posed. These are listed in order below, along with the results obtained. As a context for those results, we begin by comparing the database that was obtained with that originally envisioned for this project.

A. Observing Resources and Data Summary

At the start of this project, we were uncertain whether it would be best to use Kitt Peak's "SQIID" camera (which contains 4 PtSi arrays operating simultaneously at 4 different near-infrared wavelengths), or a new camera that would be built specifically to prototype the planned sky survey. It was eventually determined that the PtSi arrays in SQIID, combined with the electronics, were too slow to address some of the critical questions central to this project. Therefore, we used the 2MASS prototype camera, which was built in early 1992, and operated at the Kitt Peak 1.3m telescope. This camera came equipped with a single HgCdTe 256×256 array which was mounted behind a filter wheel that allowed us to observe one of 6 different wavelengths at a time. The construction of that camera was supported by NASA.

The 2MASS prototype camera came equipped somewhat differently than we had envisioned in the original proposal to this project. First, it contained a single array, not two. This was done for cost savings and technical risk reduction. Second, it contained no facility for adjusting the pixel size. Finally, we originally planned for a neutral-density filter; this eventually proved unnecessary.

The observing opportunities also differed from that outlined originally. We had originally expected that we might be able to obtain 40 nights per year at the KPNO 1.3m telescopes, and ~100 nights altogether. This amount of observing time would have been necessary to cover all six $1^\circ \times 1.5^\circ$ fields that were the original goal of this investigation. As it turned out, this project was granted only 20 nights during its 3+ year duration. However, using the 2MASS prototype camera, the observing goals were not only met but greatly surpassed.

From April 1992 through May 1993, the 2MASS prototype camera was used to survey nearly 800 square degrees over a wide variety of regions in the sky. The distribution of regions that were mapped is shown in Figure 1. Most of the data were obtained at K_s ($\lambda_{eff} = 2.17\mu m$). Additional data were obtained both in sparse, high-latitude fields and crowded, low-latitude fields at J ($\lambda_{eff} = 1.65\mu m$), and H ($\lambda_{eff} = 1.65\mu m$). Over 200 Gbytes were collected. Millions of stars and thousands of galaxies were detected.

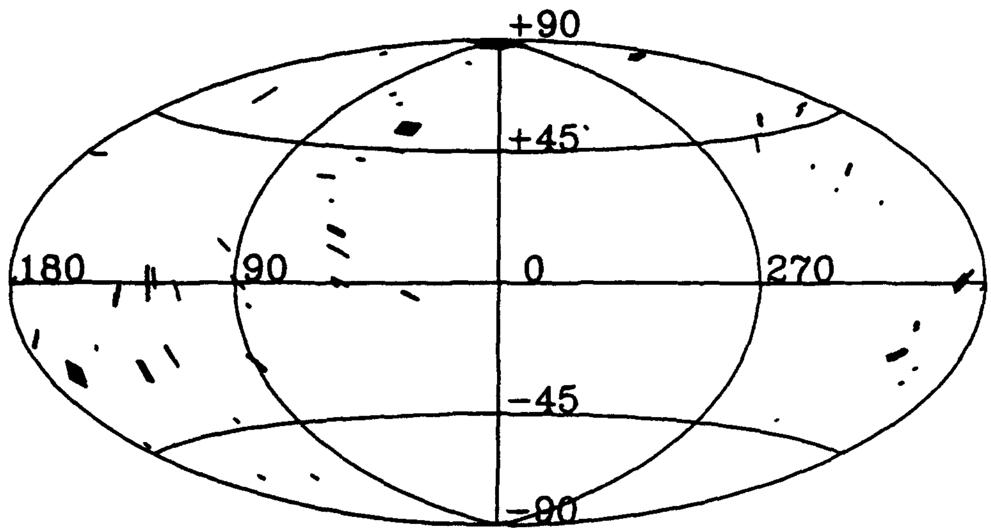

Fig. 1. Regions of the sky mapped with the 2MASS prototype camera, shown in galactic coordinates.

In late May 1994, the 2MASS prototype camera was used again at the KPNO 1.3m, this time with corrected optics and a smaller pixel size. Only 1 night was clear, but a large body of data was obtained that night. These data have not yet been reduced.

Finally, we expected originally that UMASS would do the bulk of the data reduction for this prototyping part of the project. As can been seen above, the data collected were well in excess of original expectations, completely overloading our resources. All of the data reduction was done at NASA's Infrared Processing and Analysis Center (IPAC), and UMASS activities centered on the analysis of those results. The consequences of these studies are given below.

B. Technical Questions and Answers

1. **What was the effect of moonlight on the background?**

   No effects of scattered moonlight were seen in the H or K_s images. However, images in J-band did show increased background when the telescope was pointed within $\sim 30°$ of the full moon (cf. Figure 2). This led to a moon-avoidance-angle specification for the mapping strategy for the full survey.

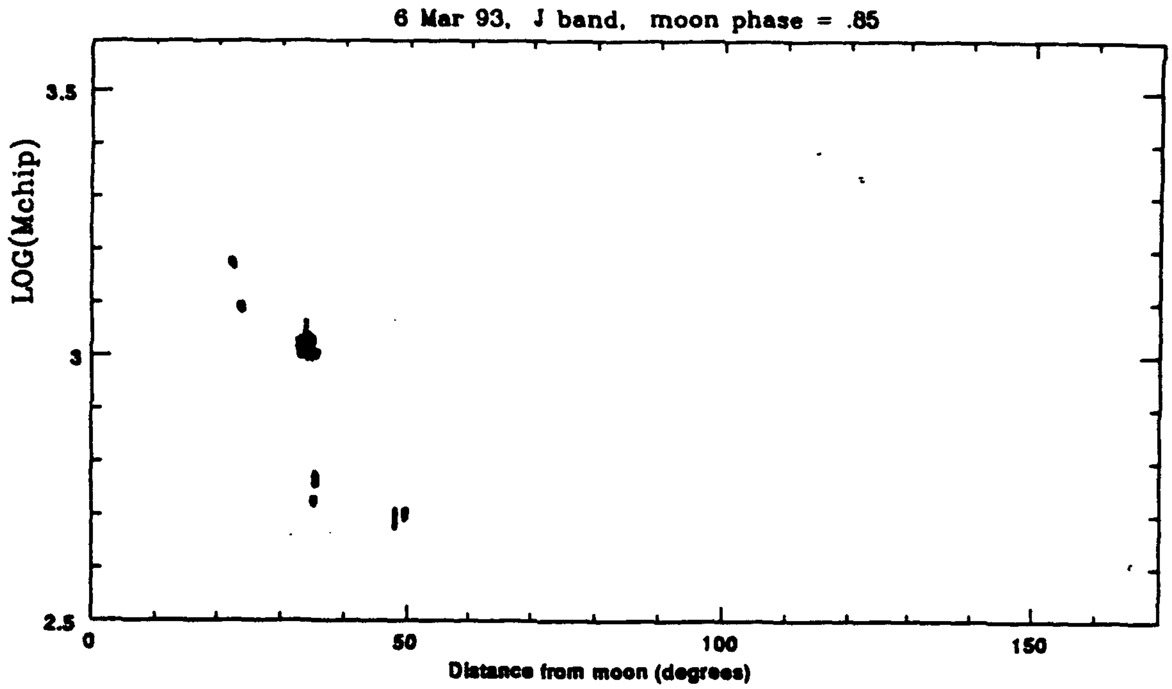

Fig. 2. Modal value of the counts as a function of angular offset from the moon, at a time when the phase of the Moon was 0.85.

2. **Is it possible to obtain a good image with the freeze-frame scan strategy?**

   The mapping strategy used with the prototype camera (and planned to be used in the coming survey) involves scanning the telescope in declination, while ratchetting the secondary in the opposite sense, such that a field is frozen in the focal plane for an amount of time corresponding to the long period of the secondary's motion. This mapping procedure is called "freeze-frame scanning." A technical concern over the use mapping procedure is called "freeze-frame scanning." A technical concern over the use of this method was whether the tilt of the secondary would cause excessive aberrations. Detailed analyses of the images from the prototype camera showed that there were serious limitations in its optics, causing large aberrations that masked any that might be produced by the tilt of the secondary. (It was for this reason that the camera was rebuilt with new optics during the winter of 1993-1994.) In the meantime, other analyses showed that aberrations due to the tilt of the secondary could be minimized by the incorporation of appropriate optics to a level below that required by the survey.

3. Do bright stars produce serious ghosting problems?

   Bright stars produced a variety of effects in the data:

   - False sources due to persistence. This phenomenon is a completely recognizable defect in the data, since the false sources occur only in the wake of a bright star, at exactly predictable offsets. It is associated with the array material, and we look forward to advances in this arena by the array manufacturers.
   - a secondary image ("ghost") reflected about the optical axis. These reflections were entirely due to the optics design in the original prototype camera and were eliminated when the camera was refurbished. This experience led to an additional specification to the survey cameras having to do with internal reflections.
   - Diffraction spikes and scattered light falsely interpreted as seperate faint sources. Such objects are obvious in source maps, and can be removed from the dataset by a variety of techniques.

C. Scientific Questions and Answers

1. How do the star counts compare with extant models of the structure of the galaxy?

The star counts at K_s-band are shown for a range of galactic latitudes in Figure 3. Along with the data, we have shown a model that is a simple exponential disk, incoporating luminous evolved stars to account for the bright sources, and significant interstellar reddening in the plane. As can be seen, this model provides an acceptable fit to the data. We conclude that the model can be used to obtain a first-order estimate of the surface density of sources anywhere in the sky. From the point of view of a physical understanding of the Milky Way itself (especially the distribution of matter affecting the dynamics), this dataset is insufficient to draw any new conclusions. Achieving that goal will require essentially the full sky coverage of 2MASS.

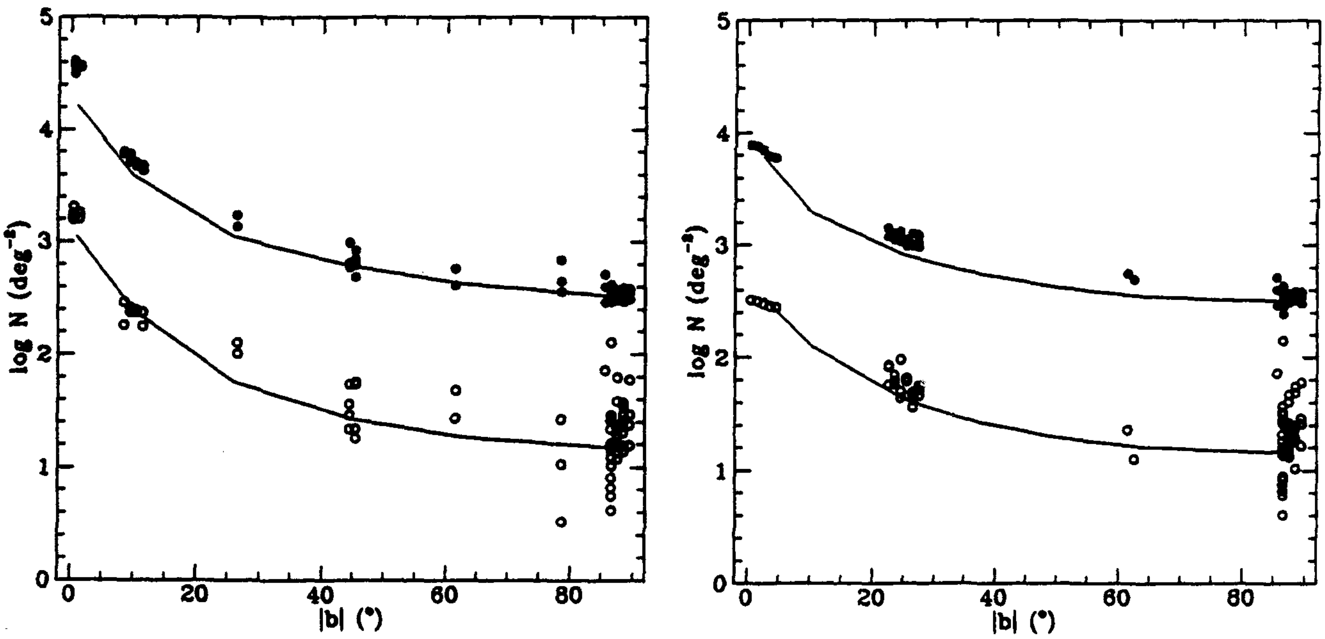

Fig. 3. ***Left:*** **Surface density of stars brighter than K_s=14 mag. (filled symbols) and stars brighter than K_s=10 mag. (open symbols), for a narrow range of galactic longitude near l=53°.** ***Right:*** **Same as the figure on the left for l=130°. The solid curve corresponds to a simple exponential disk model incorporating reddening.**

2. **What was the confusion limit?**

The simple exponential disk model described above was used to estimate the confusion limit in various regions of the sky. Confusion noise was derived assuming (as is appropriate in the galactic plane) that the source counts always scale inversely with the limiting flux, i.e., $N \propto f_\nu^{-1}$; results are given in Table 1, along with the fraction of sky that will have source densities at or above a given value based on our sky model. The match between the model and the data validates this approach.

Table 1. Confusion at various stellar densities

Density	*Beams/source*	$\Delta f_\nu / f_\nu$	*Fraction of Sky*	
(deg^{-2}	($R_e = 1.8''$)		$J < 16$	$K_s < 14$
3,175	400	1.2%	46%	16%
12,700	100	5.0%	10.5%	4.4%
25,400	50	10%	4.7%	2.5%

3. **What photometric accuracy could be achieved, and how did it depend on pixel size, integration time, and read-out rate?**

The photometric accuracy achieved on bright stars was limited by the flaws in the optics which were not taken into account in the data processing. In particular, the optics produced a much broader point spread function than was expected: at K_s, an effective aperture of 4″ was required to enclose 80% of the energy from a point source. At J, an effective aperture of 8″ was required to enclose 80% of the energy from a point source! Furthermore, the point spread function was not constant over the focal plane, and (due to aberration in the KPNO secondary mirror) changed signficantly after the telescope was adjusted for focussing.

One pipeline processing package measured the brightness of a star by fitting its profile with the point spread function. A constant point spread function was assumed (i.e., constant over the focal plane, and constant from night to night and run to run). Since the point spread function was demonstrably and dramatically variable, significant errors were found in the photometry. However, the repeatability of the photometry of stars observed in exactly the same way (e.g., at the same cross-scan position) met the original specification: $\leq$5% dispersion for all stars with K_s >12.5 mag.

The other pipeline processing package measured the brightness of extracted sources by using synthetic aperture photometry. Because of the poor optics in the original prototype camera, an aperture of $11''$ was required. This very large aperture resulted in a very high background level, and consequent loss of sensitivity. Nonetheless, for the brighter stars ($K_s < 12$), this algorithm produced data with a dispersion of <4%. The photometric accuracy of faint stars was limited by the thermal background at K_s, and airglow background at J and H. Thus, this accuracy must have been proportional to the area of the pixel and the integration time. The K_s background was significantly higher than expected, due to another flaw in the optics of the prototype camera, *viz.* a ring near the window of the camera which vignetted the field of view, and scattered excess thermal emission from the telescope onto the array.

The chip was read out at a rate of 3 μs/pixel. A slower read-out rate would not have significantly inreased the photometric accuracy, since the limitations were due to the optics. Laboratory tests (confirmed by the manufacturer of the array) showed that a faster read-out rate would have smeared the images. Thus, read-out rate was not a significant factor in the accuracy that was finally realized.

II. Publications

1. "2MASS: The 2μm All Sky Survey," Kleinmann, S. G., Lysaght, M. G., Pughe, W. L., Schneider, S. E., Skrutskie, M. F., Weinberg, M. D., Price, S. D., Matthews, K., Soifer, B. T., Huchra, J. P., Beichman, C. A., Chester, T. J., Jarrett, T., Kopan, G. L., Lonsdale, C. J., Elias, J., and Seitzer, P. 1992, in *Infrared Astronomy with Arrays: the Next Generation*, ed. I. S. MacLean (Dordrecht: Kluwer).
2. "The Two Micron All Sky Survey: Survey Rationale and Initial Testing," Kleinmann, S. G. Lysaght, M. G., Pughe, W. L., Schneider, S. E., Skrutskie, M. F., Weinberg, M. D., Price, S. D., Matthews, K., Soifer, B. T., Huchra, J. P., Beichman, C. A., Chester, T. J., Jarrett, T., Kopan, G. L., Lonsdale, C. J., Elias, J., and Seitzer, P. 1994, in *Science with Near Infrared Arrays*, ed. W. Burton, N. Epchtein, and A. Omont (Dordrecht: Kluwer).
3. "The 2 Micron All Sky Survey," Huchra, J. P., Pughe, W. L., Kleinmann, S. G., Skrutskie, M. F., Weinberg, M. D., Beichman, C. A., and Chester, T. J. 1994, in *Unveiling the Milky Way*, ed. C. Balkowsky, (San Francisco: Astron. Soc. Pacific).

III. Participating Professionals

N. B. All personnel listed below are members of the Department of Physics and Astronomy at the University of Massachusetts, except E. J. Egerton, who is an employee of Loral Infrared Imaging Systems (Lexington, MA), and who worked on the project on a consultant basis.

Principal Investigator:	Susan G. Kleinmann, Professor
Co-Investigator:	Michael F. Skrutskie, Associate Professor
Graduate Research Associates:	Lori Allen, Thomas Jarrett, Gary Kleiman, Michael Meyer, Margaret Lysaght, William Pughe
Software Engineer:	Michael Rudenko
Business Manager:	Susan Lanfare
Project Manager:	Elwood J. Egerton

IV. Interactions

1. Invited speaker at the Caltech Symposium in honor of Gerry Neugebauer's 60th birthday, "Sky Surveys: Protostars to Protogalaxies," September 24, 1992. Title: "The Two Micron All Sky Survey".
2. University of Maryland Astronomy Colloquium, April 14, 1993. Title: "The Two Micron All Sky Survey".
3. Goddard Space Flight Center Colloquium, April 15, 1993. Title: "The Two Micron All Sky Survey".

V. New Discoveries, Inventions, Patent Disclosures

None

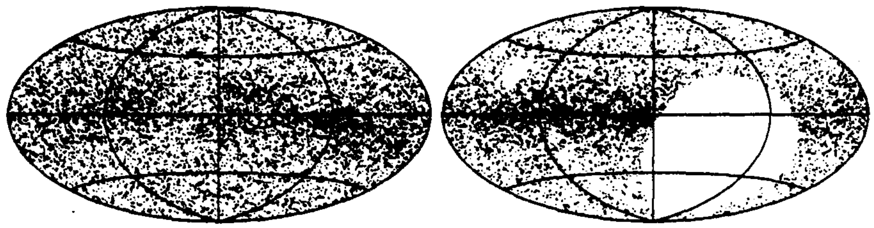

Fig. 1. The distribution of stars in galactic coordinates for (*left*) the Yale Bright Star Catalog and (*right*) the Two Micron Sky Survey.

statistical limit of K = +3 mag., sufficient to detect about 5600 stars over the region surveyed, or about 0.20 stars/deg^2. This surface density is comparable to that of the Bright Star Catalog (Hoffleit and Jaschek 1982; hereafter BSC); but a comparison of the apparent space distributions of the TMSS and BSC (Figure 1) shows that *the whole sky looks different in the near-infrared.*

This is partly due to the fact that the interstellar medium is far more transparent in the near-infrared than the optical ($A_K \simeq 0.10\ A_V$), and partly due to the fact that a different population of stars is being detected in the near-infrared: over half of the stars in the BSC are dwarfs within ~200 pc, whereas 98% of the stars in the TMSS are evolved giant stars at distances up to ~1.5 kpc.

2MASS will see evolved stars throughout the entire disk of the Milky Way, and will detect other galaxies (by virtue of their giant stars) out to distances well beyond the range in which local motions dominate the Hubble flow. The 2MASS project was designed to provide the sensitivity, uniformity, and sky coverage that would enable its use in studies of the large-scale structure of the Milky Way and the Local Universe.

Designation of the optimum design parameters for a survey of this sensitivity was initially hindered by a significant number of unknowns. For example, at the start of this project, only rough estimates were available for such key parameters as the source densities in sparse regions (e.g., the North Galactic Pole), or the region of the sky where the survey would be confusion limited. Also, little information was available on the luminosities, shapes, and other properties of galaxies that would be brightest in the near-infrared, or the variation of skyglow emission with season, time of night, elevation, and moon phase and angle. Added to these questions were large practical problems, including the need to develop a realistic solution to the mechanical requirements of covering such a large region of sky in $\lesssim 2$ years, and the need to demonstrate the feasibility of processing a data base that was expected to be $\sim 1000\times$ larger than the IRAS data base.

To address these questions, a prototype camera was built and has been used at the Kitt Peak National Observatory. This paper describes our use of that camera (§2), including an initial assessment of the quality of results. From observations of over 800 sq. deg. to date, we have measured star counts over a wide range in galactic latitude and longitude (§3), as well as galaxy counts in selected regions (§4). We conclude (§5) by summarizing our plans for implementing the full survey and providing the data to the community.

2. The Prototype Camera

The prototype camera was built at Infrared Laboratories (Tucson, AZ) during the first 4 months of 1992. It contains a single NICMOS3 (HgCdTe; 256×256) science grade array from Rockwell International Science Center, mounted in an LN_2 dewar behind a cooled, manually-controlled filter wheel which provides a means of mapping at any one of the survey wavebands.

The camera was mounted on the Kitt Peak 1.3 m telescope. Mapping was accomplished by using a technique dubbed "freeze frame scanning," whereby the telescope tracks in Right Ascension, and scans in declination, while the secondary mirror is driven in a sawtooth pattern which freezes an image on the focal plane for the long part of the sawtooth. The array was read out twice at each position, once corresponding to just (51 ms) after reset, and once 1.5 s later. Use of these two reads extends the dynamic range of the survey, allowing accurate photometry of stars as bright as $K_s = 4$ mag.

The camera has been used with a science grade array on 5 observing runs at Kitt Peak since May 1992. These included ~20 photometric nights. Data obtained from these runs have been processed at JPL's Infrared Processing and Analysis Center. The processing pipeline is itself a prototype, but has allowed a demonstration of the feasibility of the data processing task, and has provided a baseline from which one could judge the quality of the survey data.

The point spread function produced by the scanning technique is shown in Fig. 2. The major image broadening in the current configuration is due to chromatic aberration.

The quality of the data was tested by repeated observations through M92; briefly, the 1σ scatter in the photometry is 5% for $8 \leq K_s \leq 13$ mag. The repeatability of the positions of extracted sources has a dispersion of $\lesssim 0.3''$ for $K_s \leq 14$ mag.

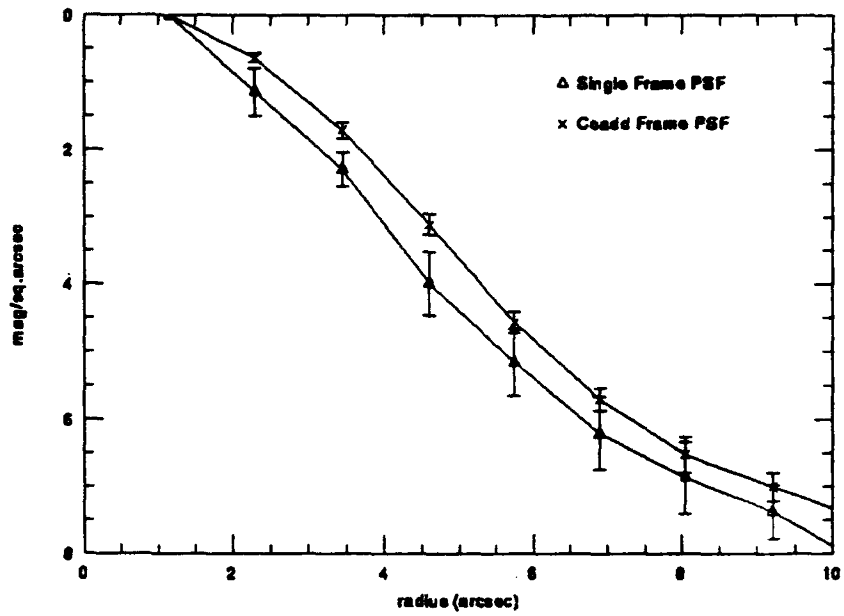

Fig. 2. The point spread function in the combination of 5 frames and the PSF extracted from the individual frames. The average PSF is much more stable than the undersampled data in any one frame and leads to accurate photometry. The average PSF is broadened in the prototype camera due to variations of the PSF across the focal plane.

3. Star Counts

Star counts in the regions observed to date, within the longitude range, $40° < l < 60°$, are shown in Figure 3. The data in the figure are compared to a simple model that incorporates only an exponential disk following Bahcall and Soneira (1981). The model also incorporates reddening due to an isothermal disk with a scale height of 100 pc and a reddening gradient of ΔK_s=0.18 mag./kpc. This simple model provides an acceptable fit in the range $0° < b < 90°$ over a wide range of longitudes.

A more detailed example of the fit of the data to integrated star counts from $5 < K_s < 14$ mag. is shown in Figure 4. for a 1 sq. deg. region near l=53°, b=0°. The quality of the fit is essentially the same in all regions analyzed to date. *Thus, a simple exponential disk model which includes reddening appears to be a good first-order means of estimating the "background" star counts, over latitudes in the range $0° < b < 90°$, longitudes in the range $25° < l < 160°$, and stars in the range $K_s < 14$ mag.*

Studies of the large-scale structure of the galactic disk using 2MASS results will rely most heavily on luminous giant branch stars, because of

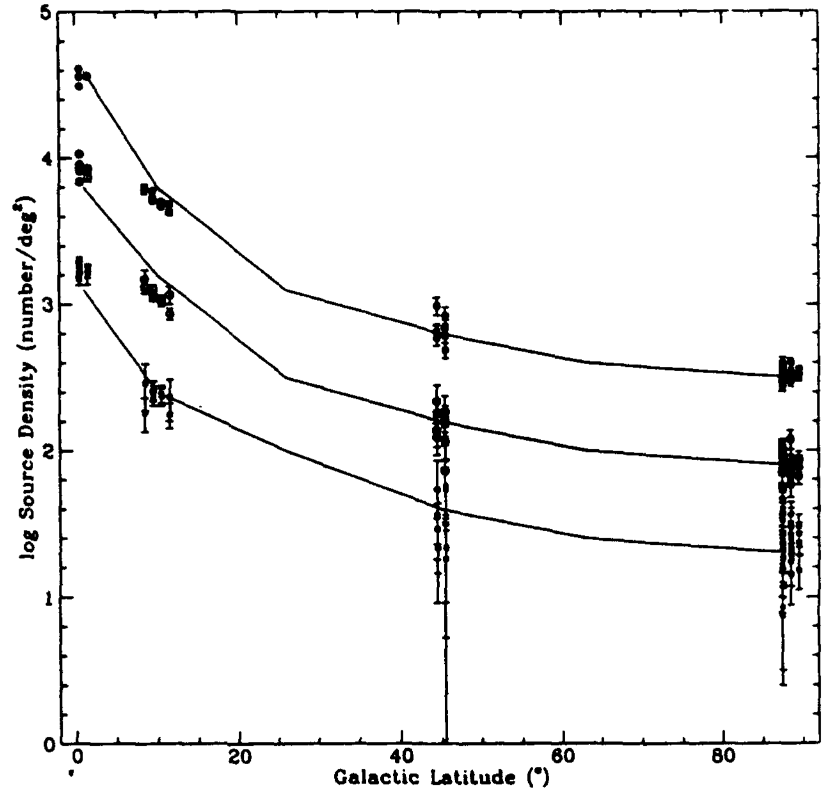

Fig. 3. The integrated surface density number of sources brighter than $K_s = 10$ (filled triangles), 12 (open circles), and 14 (filled circles) as a function of galactic latitude for the longitude range $40° \leq l \leq 60°$. The curves show the expected distribution for a model incorporating a simple exponential disk with reddening, and including AGB stars (see text).

their ubiquity, luminosity, and age. Most of these stars will be detected at $K_s < 10$ mag. because at fainter levels such stars would be seen at or beyond the edge of the disk. Accurate photometry of such bright stars is obtained by exploiting the fact that the arrays can be read non-destructively, and executing the first of two readouts of the array almost immediately after reset. The first readout provides a measurement with an integration time nearly 30× shorter than the second readout, and thereby extends the dynamic range by $\geq$ 3.5 mag. Comparisons of the photometry obtained with this technique to photometry of the same stars measured with a single element InSb photometer at Whately Observatory, show that the rms errors in the 2MASS read-after-reset photometry is $\leq$5% for stars as bright as K_s = 4 mag.

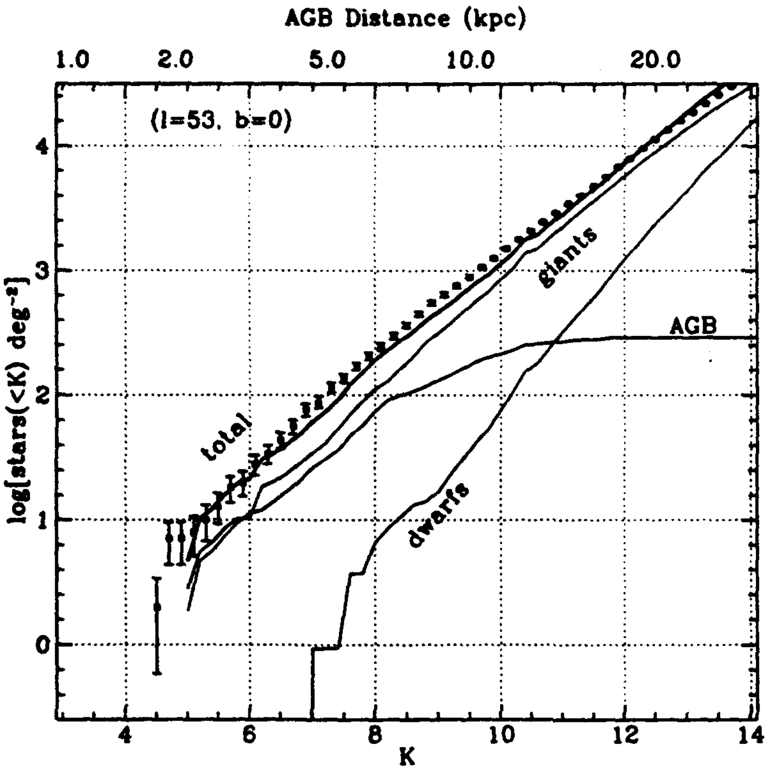

Fig. 4. Expected cumulative count density (number per square degree) in a field at Galactic coordinates $l = 53°$, $b = 0°$ together with the prototype camera results (solid squares). The contributions of counts from dwarfs, giants and AGB stars are also separately shown.

4. Galaxy Counts

Galaxies are located within the prototype camera image database by seeking objects with surface brightness gradients smaller than those of stars. (Note that this contrasts sharply with the IRAS experience, where galaxies could be distinguished by their non-stellar colors.) Since this exercise is hazardous in an undersampled image, particularly one close to the Galactic plane, we observed selected regions at middle and high Galactic latitudes to obtain a first assessment of the number and properties of galaxies that could be seen in the survey. Most of these observations were carried out at K_s, because the current optics configuration of the prototype camera provides best performance at that wavelength.

The field most intensively analysed to date is centered near ($l = 135°$, $b = -25°$), which covers about 11 sq. deg. 283 galaxies were detected to

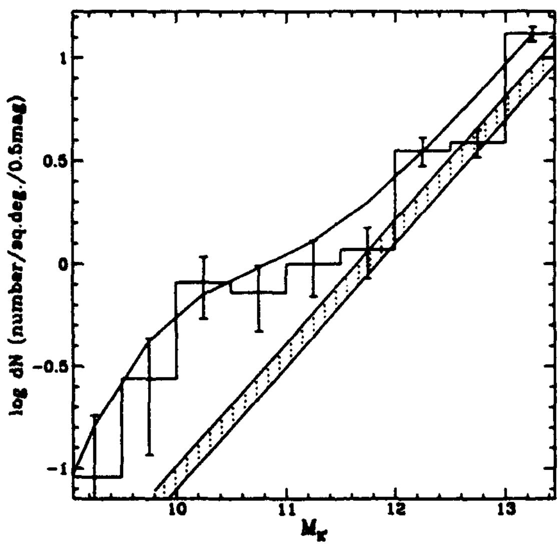

Fig. 5. The surface density of galaxies in the (l = 135°, b = −25°) field (histogram) compared with surface densities of field galaxies from Broadhurst *et al.* 1992 (shaded line). The large excess of galaxies at K_s < 11 mag. appears to be caused by the large number of galaxies concentrated at $z \sim 0.017$. A model of field counts plus supercluster members (solid line) is described in the text.

$K_s \leq 13.5$ which is 5 times more than the number found by Zwicky et al. (1961–8) down to that catalog's completeness limit of $m_B \sim 15.5$ mag. Extrapolating these counts and those from other fields against the total counts and coverage of the Zwicky catalog, and accounting for the effects of Galactic obscuration, we estimate that $\sim 500,000$ galaxies will be identified at K-band over the whole sky. The J-band census of galaxies will be even richer.

The (l = 135°, b = −25°) field is located in the region of the Pisces-Perseus supercluster, where there is a strong concentration of galaxies at redshifts $z \sim 0.017$. The differential source counts are shown in Figure 5 and are compared with galaxy counts from Broadhurst *et al.* (1992) in selected fields. Due to the excess of galaxies at $z \sim 0.017$, and because of the shape of the galaxy luminosity function, we expect an excess of galaxies near the apparent magnitude of an L_* galaxy at that redshift. As a model of the contribution from the supercluster galaxies, we show the effect of adding excess galaxies at $z \sim 0.017$. The galaxies are assumed to obey a Schechter

(1976) luminosity function, with parameters for K-band from Cowie *et al.* (1992): $\phi_* = 2.3 \times 10^{-3}\mathrm{Mpc}^{-3}$, $M_*(K) = -25$, and $\alpha = -1.1$. *The difference between the 2MASS galaxy counts in this region and those found in pencil beam surveys emphasises the impact of "local large scale structure" on galaxy counts, and the importance of measuring the space distribution of galaxies over many regions of the sky—preferably the whole sky.*

5. Implementation

The survey will be carried out on two matched telescopes to be sited at Mt. Hopkins and Cerro Tololo. Operations are expected to begin in 1996, and be completed in ~2 years.

2MASS results will be made available to the community as soon as they pass verification tests by the science team; no proprietary period has been included in the schedule. It is expected that data distribution will begin within 1.5 years of the start of the survey. The data products will include point and extended source catalogs, and an image atlas; the entire database of raw images will also be available to the community.

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